REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

PLEASE DO NOT RETURN YOUR FORM TO THE ABOVE ORGANIZATION.

1. REPORT DATE *(DD-MM-YYYY)*	2. REPORT TYPE	3. DATES COVERED *(From - To)*
03-31-2008	Final	03-01-07 - 11-30-07

4. TITLE AND SUBTITLE

INVESTIGATION OF THE ROLE OF TRANSIENT GROWTH IN ROUGHNESS-INDUCED TRANSITION

5a. CONTRACT NUMBER

5b. GRANT NUMBER

AFOSR FA9550-07-1-0463

5c. PROGRAM ELEMENT NUMBER

6. AUTHOR(S)

Eli Reshotko

5d. PROJECT NUMBER

5e. TASK NUMBER

5f. WORK UNIT NUMBER

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)

Texas Engineering Experiment Station
1470 William D. Fitch Pkwy
College Station, TX 77845-4645

8. PERFORMING ORGANIZATION REPORT NUMBER

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)

Air Force Office of Scientific Research/NA
875 North Randolph Street
Arlington, Va., 22203

10. SPONSOR/MONITOR'S ACRONYM(S)

11. SPONSOR/MONITOR'S REPORT NUMBER(S)

AFRL-SR-AR-TR-08-0408

12. DISTRIBUTION/AVAILABILITY STATEMENT

Distribution A: Unlimited

13. SUPPLEMENTARY NOTES

14. ABSTRACT

A number of topics relating to transient growth are addressed. These encompass its roots in stability theory, computation of optimal transient growth characteristics for both parallel- and non-parallel flow formulations, and the application of this information to multimode decomposition and roughness-induced transition. All of these are based on the spatial transient growth theory. For the important case of nosetip transition, the resulting transition relations reproduce the trends of the Reda and PANT data and carefully account for the separate roles of roughness and surface temperature level on transition behavior. This has now also been done for flat plates in supersonic flow and the relationship with the Reθ/Me transition criterion is examined. Further, this has led to a more general critique of the Reθ/M criterion.

15. SUBJECT TERMS

laminar-to-turbulent transition, stability theory, transient growth, roughness

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			19b. TELEPHONE NUMBER *(Include area code)*
U	U	U	U	4	

Reset

Standard Form 298 (Rev. 8/98)
Prescribed by ANSI Std. Z39.18

INVESTIGATION OF THE ROLE OF TRANSIENT GROWTH IN ROUGHNESS-INDUCED TRANSITION

AFOSR FA9550-07-1-0463

FINAL REPORT

Edward B. White, Principal Investigator
Texas A&M University
College Station, TX

Document prepared by

Eli Reshotko
Department of Mechanical & Aerospace Engineering
Case Western Reserve University
Cleveland, OH

Abstract
Over the period of AFOSR support, Dr. Reshotko and his co-worker, Prof. Anatoli Tumin of the University of Arizona, have addressed a number of topics relating to transient growth. These encompass its roots in stability theory, computation of optimal transient growth characteristics for both parallel- and non-parallel flow formulations, and the application of this information to multimode decomposition and roughness-induced transition. All of these are based on the spatial transient growth theory pioneered by the principal investigators. For the important case of nosetip transition, the resulting transition relations reproduce the trends of the Reda and PANT data and carefully account for the separate roles of roughness and surface temperature level on transition behavior. This has now also been done for flat plates in supersonic flow and the relationship with the Re_θ/M_e transition criterion is examined. Further, this has led to a more general critique of the Re_θ/M_e criterion.

Introduction
Surface roughness can have a profound effect on boundary layer transition. The mechanisms associated with single roughness elements are only partially understood while those responsible for transition with distributed roughness are not yet known. This has led to a large body of empirical information in the literature that is not fully consistent. *A possible unifying explanation for these observations lies in the mechanism of transient growth.*

In earlier papers completed under AFOSR auspices, the principal investigator and his colleague, Prof. Anatoli Tumin, showed the potential importance of transient growth in explaining the long standing blunt body paradox (Reshotko & Tumin, 2000, 2004) and have completed papers on the role of transient growth in Poiseuille pipe flow (Reshotko & Tumin, 2001) and boundary layer flow (Tumin and Reshotko, 2001). These papers are the first to use a spatial growth formulation

of these problems rather than the earlier temporal growth approach. Work continues on non-parallel compressible transient growth formulations as well as on roughness receptivity issues.

Starting with FY06, the Reshotko-Tumin grant was split into separate grants. Nevertheless, these investigators continue to work jointly on much of what is reported herein. In the current fiscal year (FY07) this work is being funded through Texas A&M University.

Objective

In this work, the relevance of transient growth to roughness effects is studied theoretically and computationally. The results will have relevance to roughness receptivity and subsequent disturbance growth at all speeds. The developed methods of analysis of optimal disturbances will be applicable to a broad spectrum of laminar and turbulent flows accompanied by the generation and development of streamwise vortices.

Approach

Extensive numerical analysis provides a database for correlation of the energy growth and such governing parameters as Mach and Reynolds numbers, temperature factors etc. The correlations can be used to straighten out the existing experimental data on roughness-induced laminar-turbulent transition. Approach to the optimal disturbances problem within the scope of parabolized stability equations (PSE) will provide a consistent inclusion of nonparallel flow effects. The latter together with the receptivity problem solution will allow a rigorous design of experiments and interpretation of experimental data on roughness-induced transition.

Progress

1. Is Re_θ/M_e a Meaningful Transition Criterion?–Reshotko & Tumin 2004 presented the optimal transient growth factors for zero-pressure-gradient flows for $1.5<M_e<6$ and $0.25<T_w/T_{aw}<1.0$. When combined with an appropriate roughness model, the results show that $Re_{\theta,tr}(k/\theta)$ is linear in Mach number for $M_e>2$, but a different line is obtained for each temperature level. The highest values are obtained for adiabatic wall conditions. Cooling lowers the transition Reynolds number. For a value of T_w/T_{aw} just below 0.2, the linear relationship above is such that $Re_{\theta,tr}(k/\theta)/M_e$ is a constant. While this suggests that the Re_θ/M_e transition criterion may be appropriate for roughness induced transition, it misses the dependencies on both roughness height and surface temperature level. By reformulating e^N transition results and flight data over sharp cones at zero angle of attack into Re_θ/M_e terms, it is shown that there is no consistency in the values or trends of Re_θ/M_e. Further examination of the meaning of Re_θ/Me shows that it is primarily dependent on density and may therefore correlate more closely with the altitude at which an entry vehicle undergoes transition. The bottom line is that Re_θ/Me has no physical basis. Transition estimation should be done using physics-based methods such as e^N and transient growth methods. A paper to this effect was presented in January 2007 in Reno (Reshotko 2007a) and an Aerospace Letter based on this study entitled, "Is Re_θ/M_e a Meaningful Transition Criterion?" has just appeared in the AIAA Journal (Reshotko 2007b).

2. Optimal Disturbances in the Supersonic Boundary Layer Past a Body of Revolution. – Following our earlier completed studies for the flat plate, the sphere (Zuccher, Tumin & Reshotko 2006) and the sharp cone (Zuccher, Shalaev, Tumin, and Reshotko 2007), a new code

has been written for the case of a body of revolution. When the new code is applied to the earlier cases of the sphere and the cone, it yields results that are identical with those of the earlier codes. The main effort in FY07 is associated with the transient growth analysis of the Stetson experiment on the flow past a blunted cone (Stetson 1983). The basic flow was generated by Dr. Heath Johnson (U. of Minnesota). A computational block to prepare the output data from the STABL package into the transient growth block was developed. The preliminary results of the transient growth indicate that the presence of the shock (when the shock layer is relatively thin) has a strong impact on the convergence of the numerical results.

3. Development of a transient growth module for PSEChem – The aforementioned non-parallel treatments of optimal perturbations are the basis for the development of a transient growth module for the PSEChem/STABL code for the STAR transition prediction program of AFRL. In order to be compatible with the parent code, the module will be constructed as a marching code. Such a formulation will utilize the local growth rate concept that was introduced in the analysis of the Reda and PANT data (Reshotko & Tumin, 2004). The significant transient growth is "subcritical" meaning that it is expected to peak before there is significant T-S growth. This work is being done under separate contract.

4. Transition Study Group Activity – Eli Reshotko continues his activity as a member of the Steering Committee of the U.S. Transition Study Group, as a participant in the STAR program and as an advisor to the HIFire (formerly FRESH-FX) flight test program.

Acknowledgement/Disclaimer
This work was sponsored by the Air Force Office of Scientific Research, USAF under contract no. FA9550-07-1-0463. The views and conclusions contained herein are those of the authors and should not be interpreted as necessarily representing the official policies or endorsements, either expressed or implied, of the U.S. Air Force Office of Scientific Research or the U.S. Government.

References

Reshotko, E., 2007a: "Is Re_θ/M_e a Meaningful Transition Criterion?" AIAA Paper 2007-0943

Reshotko, E., 2007b: "Is Re_θ/M_e a Meaningful Transition Criterion?" AIAA Journal, Vol. 45, No. 7, pp. 1441-1443, July 2007

Reshotko, E. & Tumin, A., 2000: "The Blunt Body Paradox – A Case for Transient Growth," in H.F. Fasel, W.S. Saric, eds, *Laminar-Turbulent Transition*, Springer, pp. 403-408. (Paper presented at 5th IUTAM Symposium on Laminar-Turbulent Transition, Sedona, AZ, U.S.A., 1999)

Reshotko, E. & Tumin, A., 2001: "Spatial Theory of Optimal Disturbances in a Circular Pipe Flow," Physics of Fluids, vol. 13, no. 4, pp.991-996

Reshotko, E. and Tumin, A., 2004: "Investigation of the Role of Transient Growth in Roughness-Induced Transition," AIAA Journal, vol. 42, no. 4, pp.766-770

Stetson, K.F., 1983: "Nosetip Bluntness Effects on Cone Frustum Boundary Layer Transition," AIAA Paper 83-1763.

Tumin, A. & Reshotko, E., 2001: "Spatial Theory of Optimal Disturbances in Boundary Layers," Physics of Fluids, vol. 13, no. 7, pp. 2097-2104

Tumin, A. 2006: "Biorthogonal Eigenfunction System in Triple Deck Limit," *Studies in Applied Mathematics*, vol. 117, pp. 165-190.

Zuccher, S., Shalaev, I., Tumin, A. and Reshotko, E.: "Optimal Disturbances in the Supersonic Boundary Layer Past a Sharp Cone," AIAA Jour. Vol. 45, No. 2, pp. 366-373, February 2007

Zuccher, S., Tumin, A. and Reshotko, E. 2006: "Parabolic approach to optimal perturbations in compressible boundary layers," *J. Fluid Mech*. Vol. 556, pp. 189-216.

Personnel Supported During Duration of Grant

Eli Reshotko, Kent H. Smith Professor Emeritus of Engineering, Case Western Reserve University

Edward B. White, Associate Professor, Texas A&M University

FY07 Publications and Presentations

Reshotko, E.: "Transition Issues for Atmospheric Entry," AIAA Paper 2007-0304, January 2007

Reshotko, E.: "Is Re_θ/M_e a Meaningful Transition Criterion?" AIAA Paper 2007-0943, January 2007

Zuccher, S., Shalaev, I., Tumin, A. and Reshotko, E.: "Optimal Disturbances in the Supersonic Boundary Layer Past a Sharp Cone," AIAA Jour. Vol. 45, No. 2, pp. 366-373, February 2007

Reshotko, E.: "Is Re_θ/M_e a Meaningful Transition Criterion?" AIAA Journal, Vol. 45, No. 7, pp. 1441-1443, July 2007

Honors and Awards Received

E. Reshotko, 1980 Fluid and Plasmadynamics Award, AIAA
E. Reshotko, 1984, Elected to National Academy of Engineering
E. Reshotko, 1994 Dryden Lecturer in Research, AIAA
E. Reshotko, 1999 Otto Laporte Award, American Physical Society

AFRL Point of Contact

Roger L. Kimmel, AFRL/VAAA, WPAFB, OH, Phone 937-255-8295. Met at AIAA Meeting in January 2007 and at TAMU in April 2007.

Technology Transition

In addition to potentially clarifying the role of three-dimensional roughness to the transition process in all speed ranges, the results should be helpful in suggesting optimal boundary-layer trips. This is especially important at hypersonic speeds where tripping is difficult. Under separate contract, a PSE based transient growth module is being developed for the PSEChem/STABL Transition Prediction Code under the auspices of the STAR Program.